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Sourcing Innovation: probing Technology Readiness Levels with a design framework

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ABSTRACT

Supplier-buyer exchanges are well addressed in literature except in the case of unknown objects. Sourcing Innovation, i.e. the process of finding external sources of innovation and then bringing those innovations into the firm should transform incoming unknown objects to ascribe them value. Technology Readiness Levels (TRL) have formalised the unknown in supplier-buyer exchanges in many industries for forty years but there is no evidence that they enable that transformation. We then use design theories, i.e. the Technology-Environment framework, to probe TRL through analysing ten cases combining documents analyses and longitudinal studies. We found that TRL avoid fixating on a low mature technology and are not an obstacle at genericity; however they fixate when the buyer waits a certain TRL prior exploring the new technology value. Finally TRL are unable to guide designers towards generativity notably because they embrace a definition of Environment focused on the prototyping method.

I. INTRODUCTION

The paper starts with a review on how suppliers and buyers exchange objects, specifically on the sourcing process. Purchasing management and supply chain management model exchanges of known objects, in this case sourcing refers to choosing the right suppliers an assembling firm (Swift 1995, Krause 1999, Prahinski et Benton 2004). Internal R&D plays a major role in exchanging information as it transforms it in valued knowledge (Cohen et Levinthal 1990), however sourcing is an upstream process of this absorptive capacity (West et Bogers 2014) as it defines to whom firm boundaries are open to exchange knowledge (Chesbrough 2015). Supplier and buyer may also exchange partially known objects as they are being designed in a co-development effort (Maniak et Midler 2008, Zirpoli et Camuffo 2009) which requires a specific supplier-buyer relationship where technical and economical dimensions cannot be separated and is better enacted with single-sourcing than parallel or multiple sourcing (Midler, Garel et Kesseler 1997). In all these models, supplier and buyers exchange objects with a limited degree of unknown and the panel among which innovation is sourced is quite known as well. Idea management tries to deal with these unknowns by screening ideas, but such an assessment becomes generative too fruitfully transform low-value ideas into high-value ideas (Magnusson, Netz and Wästlund 2014, Sukhov, Magnusson et Olsson 2015). Hence, theories teach us that sourcing innovation requires the capability to transform unknown objects, participating in the process of breaking the identity of objects which is a critical capability for radical innovation (Le Masson, Weil et Hatchuel 2010). Technology Readiness Levels (TRL) are a managerial innovation (Birkinshaw, Hamel et Mol 2008) which was implemented in a single organization in the 1970s and now are daily used in several industries (Mankins 2009, GAO 1999, Jean et al. 2012).. TRL are a relevant case to study sourcing innovation because the TRL assessment aims at formalizing the level of unknown of technologies in order to select among competing technologies and then contractualize which part of the unknown should be explored by the supplier (technology development) and the buyer (program). Despite the worldwide adoption of TRL in various industries, there is no evidence that they are useful in transforming the identity of objects: *Do TRL nurture or limit radical innovation?* We then review latest advances in design theories to propose a conceptual framework which will enable us to probe TRL against the notions of fixation and generativity when Technology and Environment are being designed (Hatchuel, Le Masson and Weil 2011, Kokshagina et al. 2014, Jean et al. 2015). Finally this research shall explore the three following propositions:

P1: TRL avoid to put supplier and buyer in a situation of mutual fixation;

P2: TRL overcome fixation when it is encountered;

P3: TRL steer the sourcing process so as to maximize generativity.

We leverage multiple case study methodologies to explore these propositions (Yin 2013). Data collection consists of ten cases among five organizations either based on documents or real situations in a longitudinal approach.

Results indicate that TRL definitions and procedures vary in considering either Technology or Environment fixated. But they converge on how TRL assessment is possibly generative: it generates objects in which Technology and Environment merge and knowledge on the interface Technology/Environment. Real cases show that TRL are not used when the unknown on both Technology and Environment is very high and the opportunity is being defined but once further exploration has clarified the opportunity and that investment is required to progress in technical knowledge. At this step TRL avoid fixating on a low mature technology and they are not an obstacle at genericity. However they may fixate when the buyer waits that the supplier has reached a certain TRL prior exploring the value creation if the technology was integrated. Finally TRL have a minor role in defixating compared to supplier-buyer relationship, individual interests or know-who and are unable to guide designers towards generativity notably because they embrace a definition of Environment focused on the prototyping method.

We conclude that this paper remains highly exploratory and that it calls for studies not limited to innovation theories and design theories and that quantitative studies have a major potential in deepening our results by embracing a larger panel of organisations.

II. LITERATURE REVIEW, CONCEPTUAL FRAMEWORK AND RESEARCH QUESTION

1. EXCHANGING KNOWN AND UNKNOWN OBJECTS TO INNOVATE

External exchanges in the innovation process have been broadly encouraged by literature. This paragraph tempts to summarise how these exchanges change in nature as they occur earlier in the innovation process, i.e. with greater levels of unknowns on the objects being exchanged.

a) Known objects in purchasing, supply chain management and open innovation

If the product is known and the exchanges of merchandises repeated, purchasing managers apply supply-chain principles such as choosing between single or multiple source (Swift 1995), evaluating alternative suppliers (Prahinski and Benton 2004) or involving in their suppliers development (Krause 1999). Sourcing then refers to a decision-making process in a panel of suppliers.

Internal R&D plays a greater role than purchasing when only information is exchanged because it gives a firm its absorptive capacity to transform information into value (Cohen and Levinthal 1990). In their review on external sources of innovation, West and Bogers (2014) concatenate open innovation researches in a four-phase model: (1) obtaining innovations from external sources, (2) integrating innovations, (3) commercializing innovations and (4) interaction mechanisms between. Surprisingly the absorptive capacity appears in the second phase. The very first step is *sourcing*. In fact in such streams of research, external sources of innovation are considered as a means to complement the firm’s internal knowledge in an attempt to eliminate the unknown (West and Bogers 2014). Moreover this knowledge has to be traded to be obtained from external stakeholders giving rise to incentives of various natures (Terwiesch and Xu 2008, West and Gallagher 2006). As Henry Chesbrough (2015) puts it: Open Innovation is about the outside-in and inside-out knowledge flows through firms boundaries.

b) Partially known objects and their design

To increase the rate of product launch, firms seek to reduce the time-to-market by pushing concurrent engineering to the point that suppliers and buyers can no longer rely on the traditional purchasing model of negotiating margins on fixed components but have to collaborate in the joint design of new products (Maniak and Midler 2008). End-products assemblers leave more tasks to suppliers as they buy sub-systems rather than elementary components (Midler et al. 1997). The automotive cases of A/C systems shows that buyers adopt different management practices to adapt to the amount of knowledge they have on the co-developed sub-system (Zirpoli and Camuffo 2009). Specifically when the buyer has enough knowledge on the sub-system to define architecture, specifications for components and interfaces, the rules of co-development (specifications and coordination mechanisms) are stable whereas these rules are flexible when buyers' knowledge is low. With co-development, the focus shifts from the exchange of physical components to the exchange of knowledge which requires a good supplier-buyer relationship (Sjoerdsma and van Weele 2015, Maniak and Midler 2008). Among the determinants of a good supplier-buyer relationship, trust is particularly significant because the higher is the trust between partners the higher is their investment in the partnership for innovative joint development (Bidault and Castello 2009, Bidault et al. 2007). Relationship between partners may rely either on trust or contracts; the first implies knowledge sharing the second implies knowledge transactions (Bosch-Sijtsema and Postma 2009), hence the role of purchasing managers in co-development as coordinating a joint project when a successful relationship materializes is not necessarily easier than coordinating the same project at the alliance's start (Gerwin 2004). This relationship can no longer separate technical (engineers) and economical (purchasing managers) facets of the exchange. Sales and purchasing managers take parts at various stages in the co-development to proceed the economical negotiation as value and costs are being established. Hence sourcing for co-development reduces the panel of suppliers to favour *single-sourcing* or *parallel-sourcing* over *multiple-sourcing* to foster advanced cooperations (Midler et al. 1997). However co-development restricts innovation on a limited set of performance criteria in accordance with a dominant design and prevents sources of innovation in R&D labs from being brought to the market (Le Mason and Weil 2001). Moreover the authors hint at a major role for the innovative buyer who transforms ideas in real products.

c) Sourcing unknown objects is transforming them

Open innovation sources knowledge among a large and even unknown panel while co-development focuses on few known suppliers to jointly design objects with a low degree of unknown. The new challenge for innovation theories seems then to model how to source unknown objects among unknown panels. Idea management proposes to screen ideas, i.e. unknown objects, with either intuitive or rational assessment (Eling et al. 2015, Magnusson et al. 2014). However when objects are too unknown, like radical ideas from ordinary-users, evaluation is not possible without generating mini-scenarios of implementation of the idea (Magnusson et al. 2014). Assessment is then generative, i.e. it becomes the opportunity to transform initially low-value ideas into high-value ideas (Sukhov et al. 2015). This contrasts with the traditional conception that idea assessment is a converging phase (Le Masson et al. 2011). Hence sourcing innovation embraces both divergent and convergent thinking. More generally, transforming the identity of objects by generating unknown is a fundamental capability for radical innovation (Le Masson et al. 2010). To the best of our knowledge, innovation theory has not provided explanation on how to source objects in a way that allows their transformation necessary to value creation. Studying the case of a managerial tool with a long history of formalising levels of unknowns in the exchange between suppliers and buyers should then provide answers.

2. *ORIGINS AND DIFFUSION OF TRL TO FORMALISE THE UNKNOWN IN THE EXCHANGE*

In this paragraph we try to show that Technology Readiness Levels (TRL) are a managerial innovation that has been introduced so as to provide suppliers and buyers with a formal language to contractualise the unknown and proceed exchanges. To do so we match their evolution with the management innovation process found in literature (Birkinshaw et al. 2008, Černe et al. 2013) consisting of (1) motivation, (2) invention, (3) implementation and (4) theorizing and labelling. So far, following the recommendation to separate technology development and product development in two stage-gate processes (Cooper 2006), TRL has been interpreted by innovation theories as a technology development stage-gate model (Högman and Johannesson 2013), and nowadays researchers themselves consider it a stage-gate (Fahmi and Cremaschi 2013), we will see that this interpretation is very restrictive.

a) Motivation: technology and flight coordination

Mankins (2009) explains the context at National Aeronautics and Space Administration (NASA) just before TRL emerged:

The idea of articulating the status of a new technology planned for use in a future space system was clearly stated as early as 1969. In this context, the correlation was between the then-established practice of the "flight readiness review", and a new idea through which the level of maturity of new technologies could be assessed: the "technology readiness review".

So in the context of emergence of TRL, a distinction is needed between the unknown of technologies (technology readiness) and the unknown on the spacecraft and its operations (flight readiness), giving the motivations for the managerial innovation.

b) Invention of TRL and the concept of maturity as a metric of known versus unknown

TRL were invented and first brought at NASA by the Office of Aeronautics and Space Technology (OAST) in the 1970s as a systematic tool that enables assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology (Mankins 2009). Here the focus is on technologies unknown: the less mature means the more unknown and more risk for a flight program. So TRL moved from a tool to coordinate the unknown between technologies and space programs to a selection criterion of technologies by program managers.

c) Implementation: new programs and external adopters

After Challenger Space Shuttle accident, new programs called for new technologies and improved technology maturation processes. TRL were then broadly implemented to communicate technologies status regarding space mission requirements. In the 1990s, "Integrated Technology Plan for the Civil Space Program" was the first program to use TRL both for managing internal and external technologies: *Here, for the first time, a science organization used the scale both for management of its own* *instrument technology programs, and also for communicating more effectively with technology researchers and organizations inside and outside NASA.* (Mankins 2009)

d) Theorizing and labelling nine Technology Readiness Levels

At a certain point, TRL definitions were too fuzzy among NASA and its partners, consequently Mankins (1995) established standard definitions which are still in use to date (see NASA's website). This would not have been a problem if NASA evaluated external technologies and bought them as simple merchandises, but it is absolutely necessary when labour and funds are dispatched referring to TRL as the next cases illustrate more clearly.

e) TRL growing importance in contracting the unknown as they diffuse in other industries

In the 1990s the U.S. Department of Defense (DOD) was facing major cost overruns and delays in weapon acquisition programs. It tested TRL to face these difficulties on 23 cases as reported by the General Accounting Office (1999). TRL, by giving a measure of the gap between technologies required maturity and actual maturity, showed that programs which integrated low-maturity technologies performed poorly and proved themselves as a managerial solution. We should clarify that the DOD none-the-less buy new weapons but funds the development programs lead by private contractors. Hence TRL appeared especially useful in contracting, as Jacobides et al. (2006) puts it, *who can do what* and *who gets what*:

For example, given that a technology has sufficient potential for application to a weapon system, at a minimum, an S&T [Science and Technology] *organization should be responsible for taking a technology to TRL 6 before it is handed off to a program office at the program definition and risk reduction phase. During this phase, the program manager would be responsible for maturing the technology to TRL 7 before it is included in an engineering and manufacturing development program.* (GAO 1999).

Moreover, the same report clarifies how TRL appeared instrumental in contractualising the unknown:

In the more successful cases, technology and product managers were given the authority and tools to move technology only when it was at high readiness levels. Disciplined processes provided managers credible information on the status of technologies and high standards for assessing readiness. Science and technology managers developed technologies to standards acceptable to product managers who could reject those technologies that fell short. (GAO 1999).

Finally the conclusion of the report indicates that the notions of *readiness* or *maturity* and the TRL measure the unknown and hence enable to decide to the top agency whether paying or not for this technology by making the commitment to adopt it along an acquisition program:

GAO recommends that the Secretary of Defense adopt a disciplined and knowledge-based approach of assessing technology maturity, such as TRLs, DOD-wide, and establish the point at which a match is achieved between key technologies and weapon system requirements as the proper point for committing to the development and production of a weapon system. GAO also recommends that the Secretary (1) require that technologies needed to meet a weapon's requirements reach a high *readiness level (analogous to TRL 7) before making that commitment [...]* (GAO 1999)

f) TRL worldwide importance nowadays

Similarly, GAO (2007) reported bad programs performances at the US Department of Energy (DOE) and recommended TRL adoption leading to DOE (2009) TRL methodology. They were adopted in parallel in Europe with the European Space Agency (ESA) (Mankins 2009). We find heavy proofs of recent use of TRL in nuclear industry (Li 2008, Tillack et al. 2009) as well as chemicals (Boulart et al. 2010, Fahmi and Cremaschi 2013). In the petroleum industry which has been concerned with qualification of new technologies prior to their use in production at least since DNV-RP-A203 procedures (Det Norske Veritas 2001, Johnsen et al. 2009), one author has personally been involved in the design of TRL adaptation in an oil company and as such has met with TRL users in various fields such as automotive or marine equipment (Jean et al. 2012).

We believe that TRL are understudied considering their structuring role in various industries, especially for our research question of exchanges of unknown objects and innovative sourcing, while the understanding in innovation theories of TRL is limited to a stage-gate process. At this moment, we have shown that TRL do provide a language of the unknown to enable supplier and buyer to exchange, however is this exchange effective in transforming the identity of objects required for achieving radical innovation? Design theories should provide the theoretical scaffold to analyse that.

3. A DESIGN FRAMEWORK TO ANALYSE TRL ABILITY TO TRANSFORM THE IDENTITY OF OBJECTS

a) Fixation and Generativity

Design fixation has been defined as the premature commitment to a solution to a design problem (Purcell and Gero 1996). Giving an example to the problem solver greatly condition fixation depending on designers' education (Purcell and Gero 1996). The nature of the example is critical as well and may either induce fixation (restrictive example) or help overcoming it, i.e. "defixating" (expansive examples) (Agogué et al. 2014). Design theories such as Systematic Design, Axiomatic Design, Couple Design Process or C-K theory enable to overcome fixations as they adopt formal languages which do not presume on the object being designed but can induce new fixations among these four forms: generation of alternatives, knowledge acquisition, collaborative creativity and creative process (Le Masson et al. 2011).

Intuitively, a design task produces new objects. This fundamental phenomenon has been studied in the notions of emergence in complexity theories, creativity in psychology, and finally *generativity* in formal design theories which is defined as *a systematic model of thought that both creates new objects with desired properties (not only free ideas) and provides the new knowledge necessary to warrant their existence* (Hatchuel et al. 2011).

The exchange in the unknown should then avoid fixation and enact generativity. Specifically, ***sourcing innovation should not search for the best elements (ideas, knowledge) according to established criteria but should transform a large variety of propositions without presuming on their identity in the aim to transform them with former and new knowledge in high potential objects.*** Such a definition is quite too abstract to be seized in a practical way, but once again Technology Readiness Levels give a precious hint at what could be a practical framework for sourcing innovation, i.e. the dialog between a technology and its intended environment.

b) Technology-Environment framework as design theory

We have previously described how design theories formalise generativity in the variety of fits between two spaces such as form-context, solution-problem, structure-function or concept-knowledge and how a Technology-Environment framework follows this tradition (Jean et al. 2015). Table 1 illustrates how Technology-Environment framework fruitfully applies to various design contexts.

Approach		Technology definition	Environment definition
Artefact systemic breakdown		Sub-system (e.g. radar)	System (e.g. helicopter)
Multiple organisation	Value chain	Rank N in value chain	Rank N+1 in value chain
	Employee	Technology engineer	Product manager
	Social worlds	Experts and scholars	Industry managers
Single organisation	Activity	Research	Development
	Department	R&D / R&T / S&T	Marketing / Program

Table 1: comprehensive definition of Technology and Environment in our conceptual framework

Moreover knowledge expandability is an important property of a design theory which should help distinguishing variable structures (or designed ontologies) and invariant structures (explicitly unchanged by design) (Le Masson et al. 2013). Knowledge expandability is particularly emphasized in C-K Theory as it embraces two spaces: the Knowledge space consisting of propositions with a logical status (either true or false) and the Concept space consisting of propositions both unknown and desired (Hatchuel and Weil 2009).

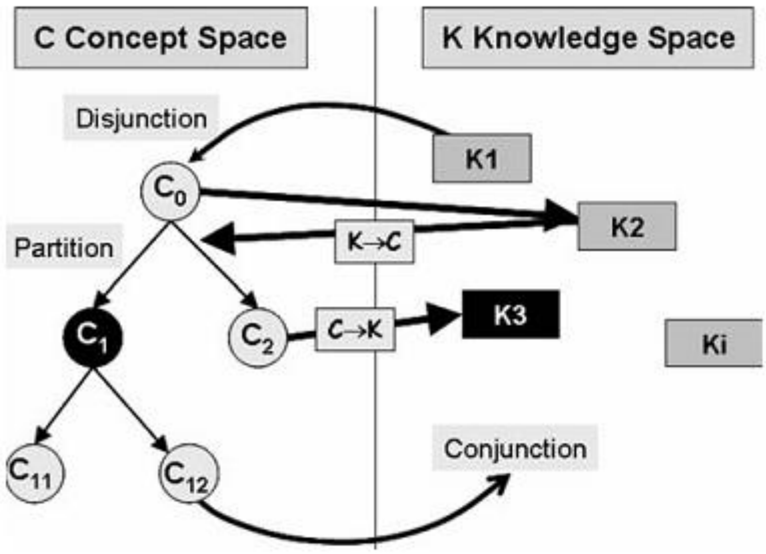

Figure 1: C-K Theory as illustrated in (Hatchuel and Weil 2009)

In previous researches which sought to maximise generativity by designing *genericity*, i.e. designing technologies which generically apply to various environments, (Kokshagina et al. 2014), the simultaneous explorations of Technology and Environment are required. Considering simultaneously two C-Ks, one for Technology and another for Environment, is then a powerful way to avoid considering either Technology or Environment as definitely invariant preventing fixation (Jean et al. 2015). The generativity of C-K theory applies through its four operators in the two C-Ks considered separately: Kt→Ct, Ct→Ct, Ct→Kt, Kt→Kt in the Technology C-K and Ke→Ce, Ce→Ce, Ce→Ke, Ke→Ke in the Environment C-K. But interactions between the two C-Ks are necessary to design the *fit* between Technology and Environment. For that, we had to define how two C-Ks can formally exchange and we find the inverse configuration as a fruitful solution (Jean et al. 2015). Intuitively, inverse C-Ks reflect a supplier-buyer bargaining situation: the buyer wants an object (Ce) that the supplier possesses (Kt). We define four new operators between the two C-K as follows.

(1) Basic operators Ke→Ct and Kt→Ce

From knowledge Environment, it is possible to describe valued properties for a technology, for instance marketers have found a need and ask engineers for a product to address it. Inversely, from knowledge on Technology it is possible to describe properties that requires an Environment to integrate it, for instance when firms seek new markets for their core technologies (Glaser and Miecznik 2009).

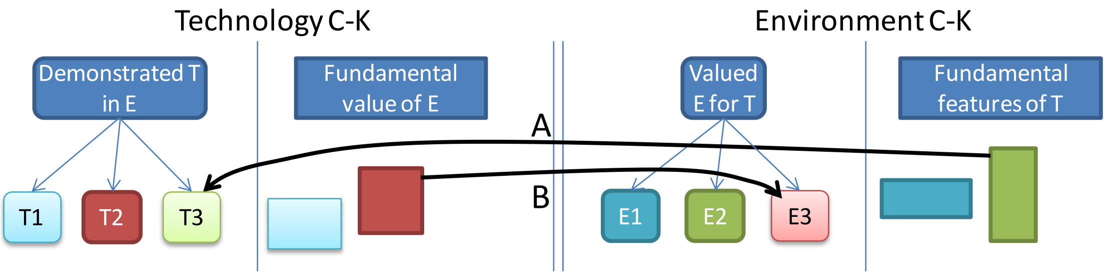

Figure 2: Basic operators A : Ke→Ct (market-pull) and B : Kt→Ce (technology-push)

(2) Advanced operators Ce→Kt and Ct→Ke specific to T-E C-Ks

When a concept is defined in the Environment from knowledge Technology (hereupon) or Environment knowledge (basic C-K theory), instead of exploring it to build this new object as an Environment, in our framework it is possible to interpret it as knowledge in the Technology C-K to increase its generativity.

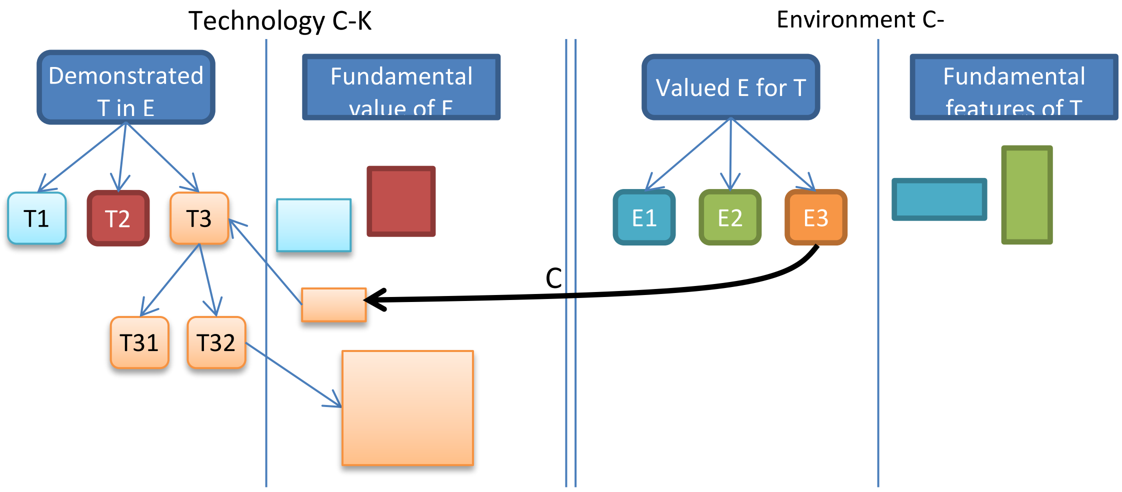

Figure 3: Advanced operator C : Ce→Kt (unknown-market pull)

Inversely when a concept is defined in the Technology, instead of exploring it to build this new object as an Environment, in our framework it is possible to interpret it as knowledge in the Environment C-K to increase its generativity. Such operator appeared crucial in highly explorative engineering projects (Jean et al. 2015).

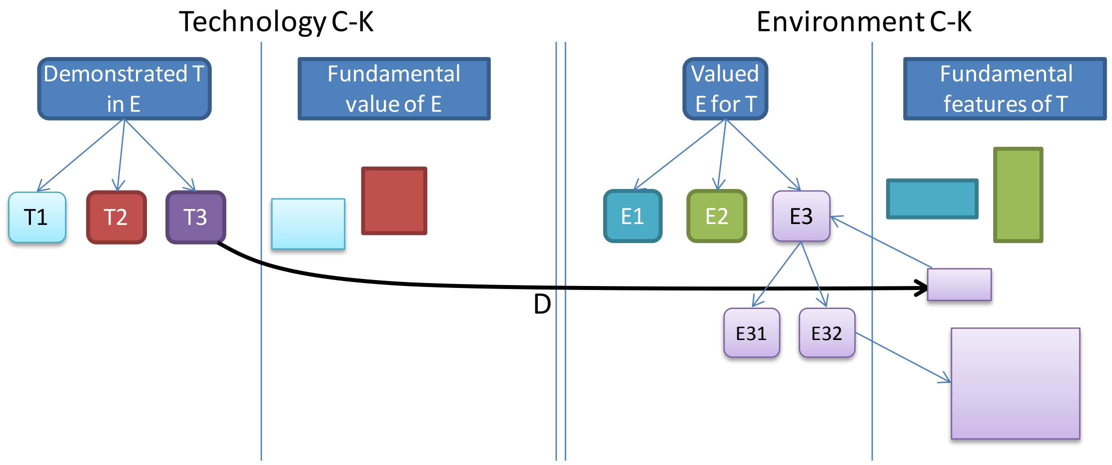

Figure 4: Advanced operator D : Ct→Ke (unknown-technology push)

c) Conditions for generativity in sourcing innovation

We have previously seen that the exchange in the unknown maximizes generativity by increasing the variety of the Technology-Environment couples explored. In our framework and according to Technology Readiness Levels, the Technology C-K models suppliers' reasoning and the Environment C-K models buyers' reasoning. Hence our model enables to understand which operator to enact depending on the situation as described in Table 2.

	Environment fixated	Environment unknown - innovative buyer

Technology fixated	A dominant design is incrementally improved based on stable criteria, Ke→Ct: the supplier adapts existing technologies to slightly pushed specifications from the buyer Kt→Ce: the buyer tries to slightly improve its product performances Ce→Kt maintains fixation as Ce is incremental, supplier's opportunity for improving existing T Ct→Ke maintains fixation as Ct is incremental, buyer's opportunity for improving its products	New products are on the verge to be developed by the buyer. TRA help Ke→Ct not applicable for no Ke yet Kt→Ce: the buyer's ambitions are pushed or focused in a relevant direction Ce→Kt defixates T, the supplier can design new technologies which will be required by the buyer Ct→Ke: E takes future technologies into account at earliest stages enabling radically new architectures
Technology unknown - innovative supplier	New technologies are on the verge to be developed by the supplie TRA required Ke→Ct the supplier's ambitions are pushed or focused in a relevant direction Kt→Ce not applicable for no Kt yet Ce→Kt technologies get more chances to create value in the buyers new products Ct→Ke: defixates E, the buyer can design new products which will benefit from new technologies	Un-established value chain and joint design of new architectures avant TRA Ke→Ct: the supplier identifies opportunities of new technologies Kt→Ce: the buyer identifies opportunities of new products Ce→Kt: the supplier anticipates potential new product architectures Ct→Ke: the buyer anticipates potential new technologies

Table 2: Effects of Ke→Ct, Kt→Ce, Ce→Kt and Ct→Ke depending on buyers' and suppliers' fixation

d) Research Question

Our literature review indicates the high stakes around sourcing innovation: it needs high level of unknowns to generate new objects but theories are very limited in models to deal with high levels of unknown. It also shows that for more than fifty years Technology Readiness Levels (TRL) have been used by practitioners in various industries to formalize and enable the exchanges of unknown objects. They have proved to be effective in preventing delay and cost overruns, but to the best of our knowledge no one has raised the question of their effectiveness in enabling firms to renew the identity of objects. In simple words, are TRL effective for radical innovation? Finally our design framework enables to diagnose a situation between a potential buyer and a supplier of a technology and prescribe actions to enact generativity in the process. Hence, in order to clarify whether or not TRL are an effective tool in sourcing innovation, we would like to explore the following propositions:

Proposition 1: TRL avoid to put supplier and buyer in a situation of mutual fixation

Proposition 2: TRL overcome fixation when it is encountered

Proposition 3: TRL steer the sourcing process so as to maximize generativity

III. METHOD AND RESULTS

A. RESEARCH DESIGN AND DATA COLLECTION

This research is a multiple-case study analysis (Yin 2013). This method of inquiry is relevant to our research question because, at this stage of theoretical understanding, construct validity requires qualitative investigation rather than statistical validation. The TRL literature refers to established value-chains that can be modeled as [technology suppliers]-[product assembler]-[product acquirer and operator]. Then it would be relevant to capture viewpoints from all three levels of such value chains. Moreover, this research combines longitudinal studies in two firms, where the searcher could attend meetings and conduct semi-directed interviews, and documents analyses.

Case title	**Industry**	**Position in value chain****	**Start with TRL**	**Case summary**	**Data (detailed list of documents in appendix)**
NASA	Space and aeronautics	Acquirer	1960s	Procedures study	Description of TRL, engineering procedure, official papers
DOD	Defence	Acquirer	1990s	Procedures study	Description of TRL, TRA methodology, reports of innovation projects
DOE	Energy	Acquirer	2000s	Procedures study	Description of TRL, methodology,
O&GP	Oil&Gas	Assembler	2012	Procedures study	Description of TRL, attendance to 3 TRA of external technologies
O&G1	=	=	=	Evaluation-Qualification of a Technology for generic applications	Attendance the one-day workshop among 7 months longitudinal study
O&G2	=	=	=	Evaluation-Qualification of a Technology for a producing oil field	Attendance to the one-day workshop among 7 months longitudinal study
AeroP	Aeronautics company	Tier-one supplier	2005*	Procedures study	Description of TRL, participation to 2 exploration projects earlier than formal TRA

Aero1	=	=	=	Start of a smartphone app to collect ideas from external organisations	Presentation of the app meeting, ideas assessment meeting, interview with app manager
Aero2	=	=	=	a supplier proposes a new technology in early development to integrate in products	25 months longitudinal study, attendance to 60 meetings
Aero3	=	Tier-one and tier-two suppliers	=	Supplier and buyer within the same holding launch a joint exploration project	25 months longitudinal study, attendance to 26 workshops and meetings

**the value chains we investigate can be modelled as suppliers-assembler-acquirer
*The organisation was created from the merging of two companies in 2005, only one used TRL. Then other companies already using TRL joined the conglomerate. During this research the organisation has a general procedure and all business units are familiar with TRL.

Table 3: Summary of the cases of this research

B. DATA ANALYSIS AND RESULTS

4. DOCUMENTS ANALYSIS

To explore our *Proposition 1: TRL avoid to put supplier and buyer in a situation of mutual fixation***,** we compare the TRL procedures, i.e. how actors within organizations are asked to do when they face a sourcing situation.

a) TRL definitions analysis

The detailed analysis is in appendix, Table 4 presents a summary.

Do TRL definitions embrace multiple alternative (Generic approach) or single (fixation)					
	…at NASA?	…at DOD?	…at DOE?	…at O&GP?	…at AeroP?
…technologies…	Generic	Fixated	Fixated	Generic then fixated	Generic then fixated
…environment…	Generic then fixated	Fixated	Fixated	Generic then fixated	Generic then fixated

Table 4: Synthesis of the analysis of TRL definitions

b) Procedures and recommended practices analysis

Here we present a summary of the analysis. The key citations leading to this conclusions are reported in appendix (when not confidential).

(1) NASA

TRL are one tool of systems engineers who are broadly encouraged to produce multiple competing designs and to select them notably on the basis of technologies maturity which is formalised by assigning TRL during Technology Assessment. System engineers should ensure that technology development and programs are well coordinated so that overall scientific requirements of the mission are met and Technology Assessment serves this goal notably by identifying unfeasible requirements at program levels. The fuzziness of the TRL definitions is instrumental in maintaining generativity at Technology Assessment: every Technology Assessment should start by defining use terms to assign TRL because their general definitions need to be adapted to particular cases. So the fixation on both Technology and Environment in the TRL definition is temporary in order to lead efficiently Technology Assessment. For instance when considering a Technology which TRL is high (>5) in a previous environment but unknown in the environment being designed, the rule is that TRL drops to 5, 6 or 7 depending on the results of the analysis. It seems then that TRL are compatible with generativity if a certain heuristic approach is adopted during TRL assessment.

(2) DOD

In this organisation, alternative technologies should be envisaged to mitigate a given risk revealed through Technology Readiness Assessment or as a result of a multiple design approach. The latter is highly formalised, again as part of systems engineering practices, in the Alternative System Review. The procedure highlights the collaborative approach of Technology Readiness Assessment, but there is a blur on whether the technology supplier is included in the review for Subject Matter Experts should be independent from the program and have no conflict of interest. Finally only critical technologies are reviewed among a set of technologies whereas at NASA Technology Assessment can be envisaged for a single technology in order to define the environment. Consequently, TRL are not envisaged for sourcing innovation at DOD but are mainly a risk management tool in later stages which differs from NASA where there should be considered in the definition of the main architecture.

(3) DOE

DOE is even more focused on risks. The Technology Readiness Assessment procedure at DOE is surely fixating: concurrent technology developments are seen as additional risks, developing alternatives should be the result of back-tracking due to unmet requirements, technology are selected (sourcing innovation requires transformation in our framework) to meet predefined requirements (joint definition is more generative as observed at NASA). However *DOE-wide model*, presently wider than Technology Readiness Assessment, is claimed to be more generative: technology development addresses specific technologies for one or more potential identified applications and demonstrates them for each specific application. An example of this wide model is a review of alternatives.

DOE evokes the potential use of a *TRL Calculator*, that is a software which automates TRL assessment based on its users' answers to the question it proposes. The procedure warns about its potential inaccuracy and clarifies that it was originally developed to be used *within* a research laboratory. If the results provided by a TRL calculator would be used in the interfacing between buyer and supplier, whether the transformation of the objects and the creation of knowledge could occur remains unanswered. Overall, regarding TRL assessment and not the wider managerial system, DOE procedure is more fixating than DOD procedure which is more fixating than NASA.

(4) O&GP

O&GP has created its TRL definitions by adapting NASA definitions. As described here upon, TRL descriptions at O&GP envisage several environments until TRL 7 where more focus is needed to achieve operating conditions and then several (similar) environments again. Moreover, O&GP procedures are unique in including the dimension of stakes, i.e. the opportunity behind the technology. We should conclude that TRL assessment reflects a strategy of developing generic technologies. In the other cases TRL design the couple [best technology, intended environment], in this case TRL design a generic technology [considered technology, opportune environments].

(5) AeroP

AeroP has created its TRL definitions by adapting NASA definitions as well. The procedure describes TRL assessment as a cyclic activity in technology development. It concerns *critical technologies* which definition differs from the previous cases. At AeroP critical technologies should confer a strategic advantage. The criticality does not refer to functionality of the target environment but to the potential benefits. The procedure envisages demonstrating several technologies at a time for several environments. It also states that the requirements for the technology from the intended environments might be unknown, and that the experiments should be conducted so that later extrapolations of results are possible in the perspective of matching them with requirements when they are defined. We should conclude that the TRL procedure at AeroP is part of the technology development process which is aimed at enacting generativity through generic technologies.

5. *REAL CASES ANALYSIS*

Proposition 2: TRL overcome fixation when it is encountered and *Proposition 3: TRL steer the sourcing process so as to maximize generativity* are explored through analyzing real empirical situations. We analyse the dynamics of the collaboration as operators between Technology C-K and Environment C-K as described in Table 2.

a) O&G1 and O&G2

Both cases are part of the Evaluation-Qualification process of technologies. The process is part of risk management prior integrating new technologies to new oil fields, ideally it is repeated several times from conceptual design to production. The supplier, the innovation manager steering the Evaluation-Qualification, the target field representative and required experts participate to the process. In short the process entails five phases: understanding of context, stakes and design; maturity assessment, failure modes effects and criticality analysis (risk assessment); action plan edition and execution. Technology Readiness Levels are used in the maturity assessment.

In O&G1, the supplier first contacted the oil company to present their game-changing technology. It would have significant impacts on overall design and operations of oil fields. The process gathers the supplying technology engineer and research manager, the innovation manager, an oil field architect of the oil company, and a consultant for one day to conduct maturity assessment and risk assessment. No specific oil field is expected to integrate the technology so the Evaluation-Qualification is lead in a generic way and the architect partially participated as expert rather than stakeholder.

The result of this Evaluation-Qualification is that the technology has high potential for value creation and deserves interests from various stakeholders, but considering its impact on operations no concessions are possible on TRL and for the moment the TRL of this technology is too low. The innovation manager considers that maturity assessment compensates for the missing knowledge required to identify exhaustively risks and hence is decisive in comparing technologies and deciding whether integrating them. A low TRL indicates that uncertainties that cannot be identified clearly enough to be addressed in the current state of knowledge remain. Uncertainties resolution plan is the main output of the process and combines outputs of maturity assessment and risk assessment.

In O&G2, an oil field in production is facing expensive problems and sponsors an Evaluation-Qualification to benchmark solutions and integrate one with controlled risk. The attended one-day workshop concerns one solution and is aimed at proceeding maturity assessment and beginning risk assessment. It starts with a presentation of the oil field with accurate quantifications of the problem by managers and engineers who sponsor the Evaluation-Qualification. Then the assessment starts on each element of the technology breakdown that had prepared the consultant. The innovation manager considers that maturity assessment identifies vague risks and as such is an input to risk identification enabling to concentrate on relevant risks. The risk management plan is the main output of the Evaluation-Qualification as it defines technology development efforts needed prior use. A show-stopper had been found for a competing technology as soon as maturity assessment stopping the process, the low TRL formalize the decision once it has been taken more qualitatively than based on the number.

These cases illustrate that in this organization TRL assessment is practiced either in [Technology fixated with large unknown, Environment unknown] or [Technology alternatives with few unknown, Environment fixated and known] situations. Then TRL avoid fixation on a low mature technology. The other fixations are results of other reasoning than TRL assessment. The cases also reveal different conceptions of TRL assessment: either it measures the risk that unknown-unknowns (blind spots) remain or it makes a start for an effective risk assessment. The latter reveals distrust of the ability to measure the remaining unknown.

b) Aero1

A network of *innovative buyers*, one per business unit from purchasing teams, has been set and is coordinated by the central *open innovation manager*. Their mission is explicitly to source innovations outside the firm. They all have access to a smartphone application from which suppliers submit ideas and are asked to vote for valued ideas and explain why. In a first time, they met in order to review all the ideas for the very first time. In a second time they debriefed on their experience of the new process and tool.

(1) Review of the sourced technologies

Most input ideas among 17 were considered as new technologies except 4 which could not be understood at all or promoted the supplier without innovative propositions. It should be noticed that TRL were not assessed despite they are in use in all business units. Some jokes were made about the low TRL. The open innovation manager had prepared another assessment table but it was not completed because it was time-consuming and because most criteria could not be assessed as the ideas were too unknown among participants. Each innovative buyer had been asked to consult experts concerned by the proposed technologies and to vote in the name of their entire business unit. Two of them had done so, the three other attendants had voted on their own. So each innovative buyer represented a potential environment for the new technologies. Except technology 3 and 7 which had already been collaboratively explored in one business unit, the level of unknown from the suppliers' viewpoint were and remained unknown. Consequently the initial situation is [Technology unknown; Environment unknown] according to our framework Table 2. As summarised in Table 5, at the end of the meeting, numerous ideas have been matched with a potential environment (Ct→Ke→Ce). However matching just indicates that a potential will be explored by interviewing a relevant expert (Ce→Ke to be done). Technology 1, 3, 6, 7 and 14 were transformed as additional uses to the initial description were defined either before with experts or during the review (Ct→Ke→Ce). At the moment of writing, we had no data on which technologies developments were pursued but that would give additional indications on the impact of generativity in the next stages of sourcing innovation.

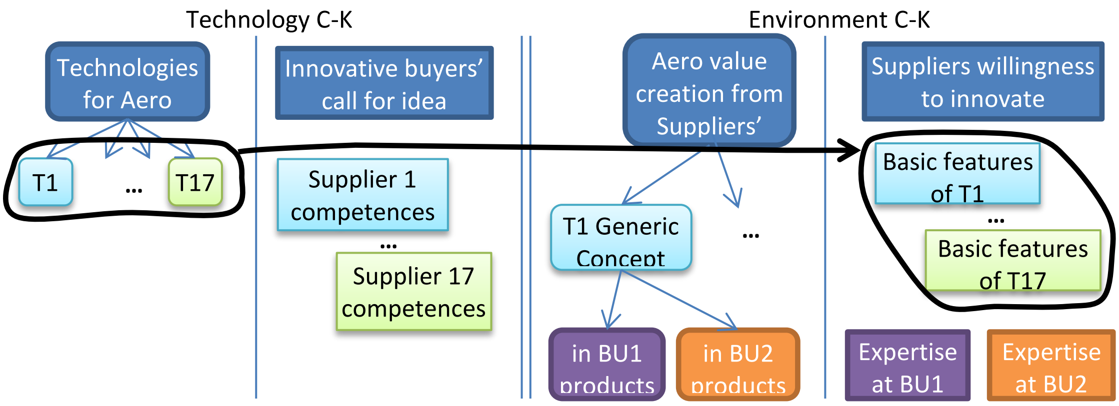

Figure 5: Technology and Environment C-Ks model of Aero1

Technology ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Environment matched	1	2	4	x	0	3*	2	x	x	1	2	0	2	2	1*	1	x

*environments represented by innovative buyers who could not attend the meeting

Table 5: Summary of idea sourcing by innovative buyers in Aero1

(2) Debriefing of innovative buyers' experience

One innovative buyer reported that the process of meeting with the experts was threatened as experts lose patience for many ideas are too incomplete to be assessed or even intelligible. The other declared that without this process he would have liked three ideas but this process enabled to define the value on three more ideas. The participants collectively concluded that meeting with experts prior this review was critical in the ability to identify the value of ideas. To ensure that this principle is met the next times, the open manager stated that the next reviews would be limited to a set of technologies belonging to a same domain of expertise so that concerned experts can fruitfully participate.

Finally innovative buyers collectively concluded from this first experience that sourcing innovation with the smartphone application and the process in progress mainly deals with redirecting a technology to the expert who has the knowledge to make use of it (Ct→Ke and Ke→Ce).

c) Aero2

An engineer learns about an external emerging technology which could be developed and commercialised and presents it to another business unit (Kt→Ke) who identifies three potential environments (Ke→Ce). Few calculations are lead with an external research center (Ce→Kt) confirming potential value in two environments but declining one (Kt→Ke→Ce). Later potential buyers realize that, in place of a former technology the new one would degrade one requirement (Ce→Ke). The exploration stops, no TRL has been formally assigned to the technology.

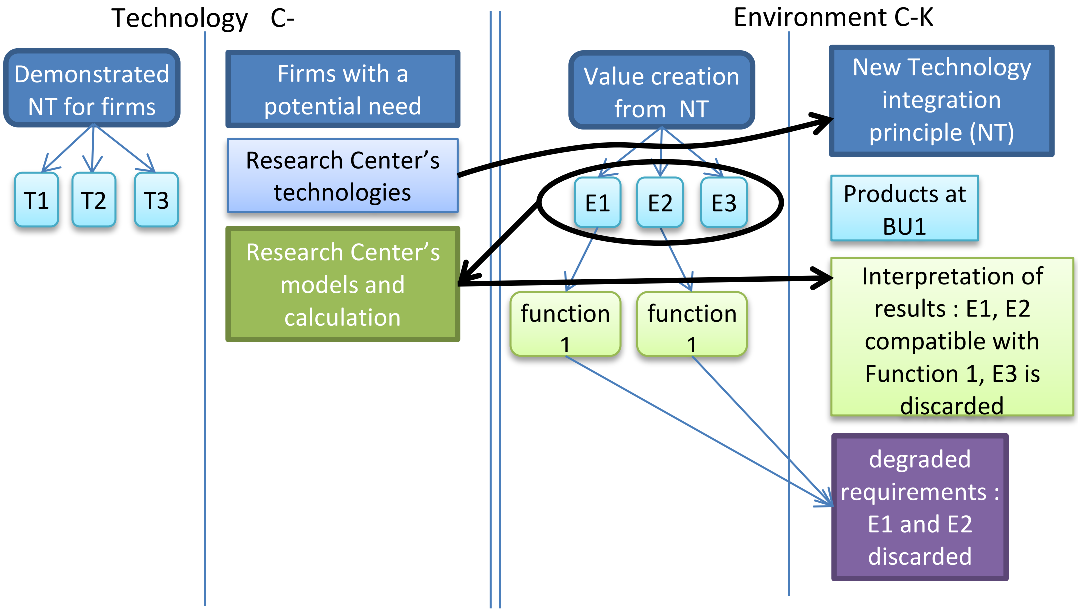

Figure 6: Aero2 first unsuccesful exploration using only

An innovative design method is conducted during one year involving all the business units. Among output concepts, a generic concept is matched with the new technology and the previous explorations are presented to the Innovation Department to grant a budget. The latter ask for more specific applications among existing products, the estimated TRL is 3-4 which is satisfying. The generic concept is presented in another business unit, once the basic principles and the average efficiency shared (Kt→Ke), the project manager identifies a potential environment but the project is too advanced and cannot bear the required modifications (Ce→Ke). Meeting with another expert from another business unit, the latter identifies new applications in its products (Kt→Ke, Ke→Ce). These applications are presented to the research steering committee in the business unit and receive approval. Despite the Innovation Department demand, experts of the identified Environments and their managers resent to explore the value creation if the technology was integrated (Ce→Ke blocked) arguing that its performance and maturity should be confirmed first (fixation on Ct at the expense of Ce, or waiting game). A seminar is organized involving three phases Environment, Technology and debriefing. In step Environment, the experts from three different business units share about the applications value and hurdles (Ke→Ke) and what has to be learned on this new technology (Ke→Ct). In step Technology, a supplier presents its early development efforts on the technology and their ambitioned performance. This performance is translated by experts to fit their own criterion (Ct→Ke) and happens to be satisfying (Ce→Ke) and is latter used to precise outcomes for this technology (Ce→Ke, defixation has occurred despite the performance ambition is not contracted). Several other experts in the business units are interviewed on both demonstration and value creation of the technology.

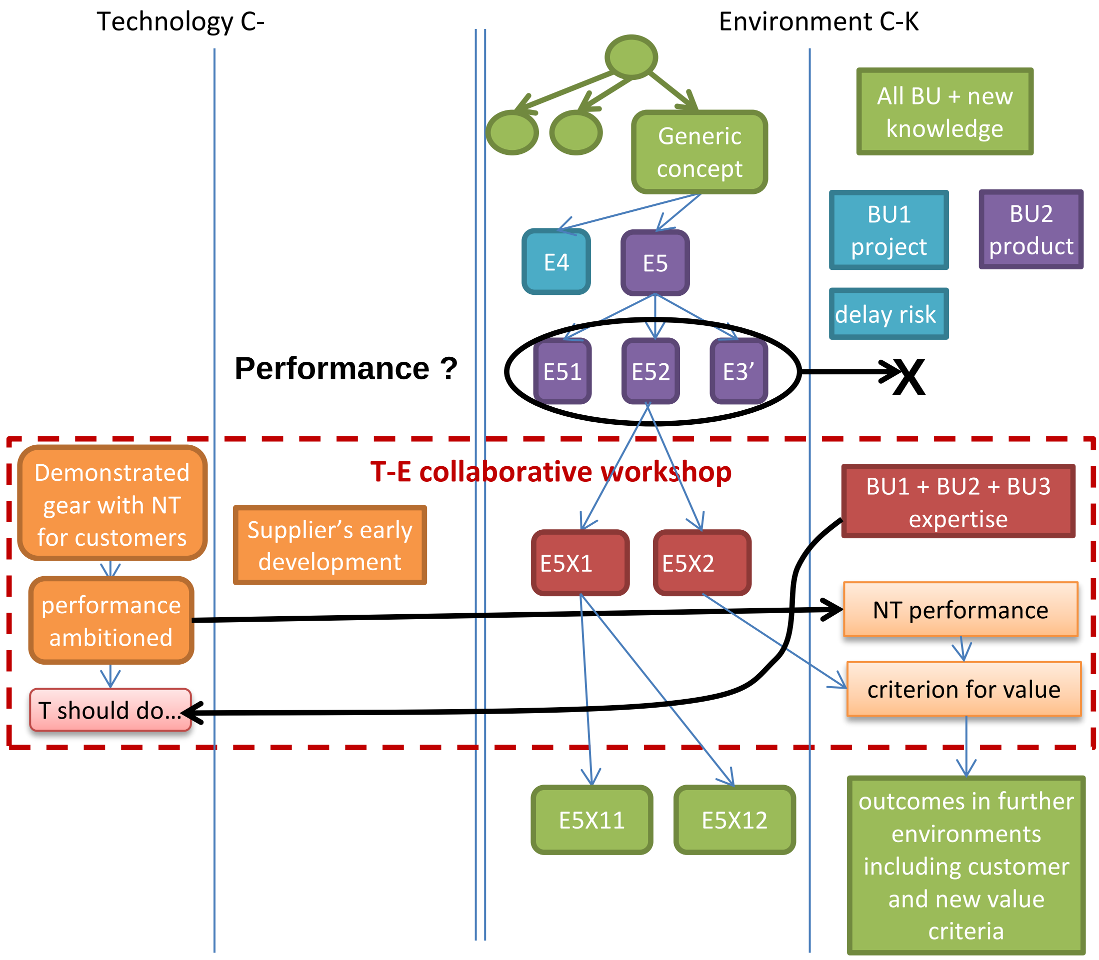

Figure 7: Aero2 defixation thanks to Ce→Kt advanced operator

A gate-meeting allows budget for a feasibility study despite TRL are quite low (the study would achieve TRL2). At the gate a planning is presented with the milestones for the technology, i.e. the intended dates for passing from a TRL to the next and the resources to achieve these miles stones (hence using TRL as stage-gate model). It should be noted that a single TRL process is defined while four environments are envisaged, however they present different requirements for the technology which might perform differently in each environment. At time of writing the first milestone (TRL2) has not been reached, the first formal TRL assessment is yet to come. We should add that the feasibility study involves two suppliers of the Technology, one on transactional-based relationship the other on a trust-based relationship. In the transactional-based relationship the supplier is committed to providing knowledge in exchange of money which occurs without major difficulties. The technology has reached TRL4 in the research center but their assessment is not relevant to the company. In the trust-based relationship, the supplier begged for requirements to focus its studies and avoid useless spending while the buyer waited for a certain performance to be demonstrated to work on the requirements to avoid useless spending as well (mutual fixation, waiting games).

This case suggests that organizations who adopt TRL have difficulties to explore the unknown opportunities hidden behind unknown technologies. A rational explanation might be that experts are used to the rule that programs do not integrate technologies of TRL lower than 4, discouraging them from spending time on such technologies. ***From a design point of view, this difficulty implies a fixation on Technology at the expense of Environment and we should highlight the role of the Ct→Ke operator in overcoming such fixation. In a trust-based relationship, supplier and buyers mutually fixate by waiting the knowledge creation from the other (either Ct→Kt or Ce→Ke and knowledge sharing) unless advanced operators (Ct→Ke or Ce→Kt) stimulate them.***

d) Aero3

An innovative design method is conducted during one year involving all the business units. Among output concepts, many are disruptive in the sense that they change the identity of objects within the whole value chain: airports, planes and their components are transformed in a set of unknown objects (Both Technology and Environment are unknown). After the collective exercise, a single business unit BU1 tries to explore one of the concepts (drafted T-E fit or Ce-Ct couple) and asks the Innovation Department for a budget to do so. It seems that no budget can be granted because the TRL of the enabling technology is too low (*estimated* TRL lesser than TRL3) and performances not sufficient (negative Ct→Kt). However the innovation department organizes a meeting with another business unit BU2 which has related expertise (activation of know-who): once they are told the ambition (Ce→Kt), they declare having previously explored technologies (Kt→Kt, TRL2 but more in other industries) which performance would satisfy basic requirements.

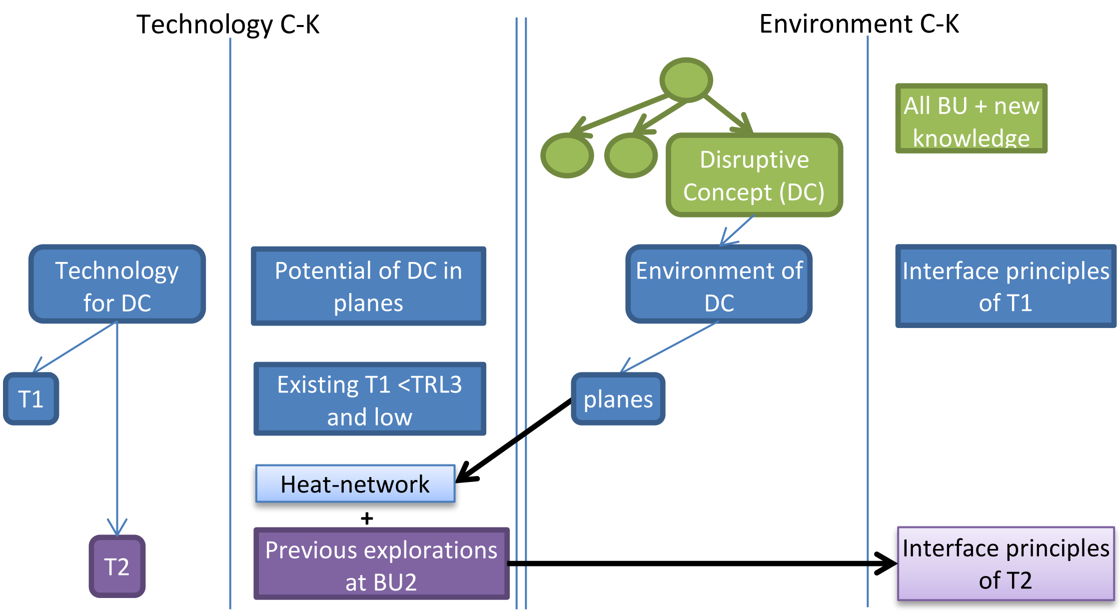

Figure 8: Aero2 defixation by exploring new technologies

More business units who could participate as experts and capture value if the concept were implemented are consulted (know-who activation) and a collective one day innovative design workshop is organized involving four business units and animated by the Innovation Department as follows: presentation of Technology know-how, presentation of Environments related problems, concept generation. While refinement of the initial concept was expected, much more generativity is enacted during this collaborative innovative design workshop. Buyers and suppliers suggest concepts to each other (Kt→Ce, Ke→Ct) and for themselves (Kt→Ct, Ke→Ce) among five main themes (i.e. Technology-Environments fits).

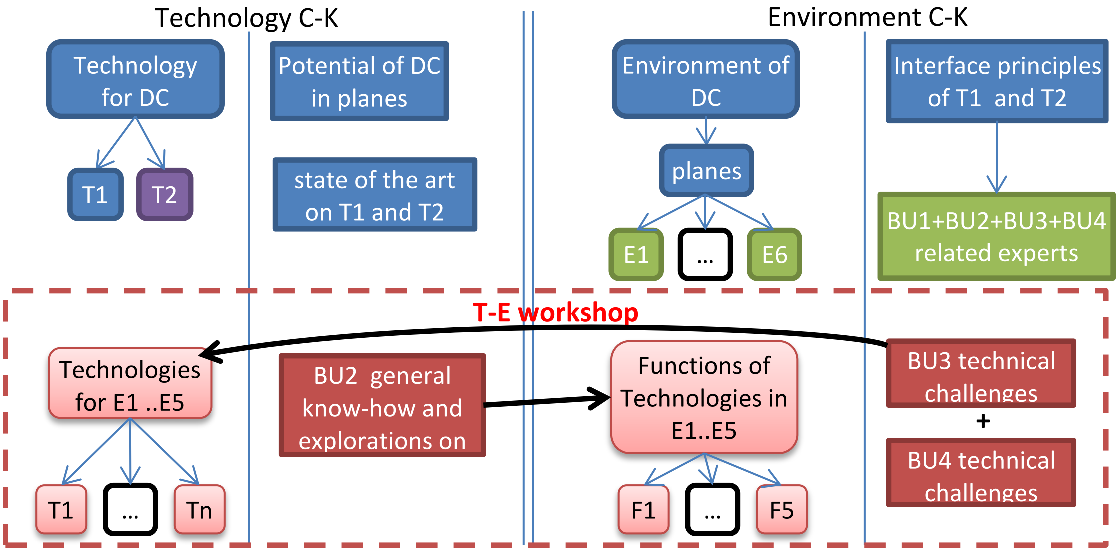

Figure 9: Aero3 generative T-E workshop

BU1 and BU2 associate to fixate on a particular concept but need one specific business unit BU3 as buyer to conduct this project. At one occasion to present the project, BU2, who was the supposed supplier of the technology, complains that BU1 one overestimates the TRL they have reached to find sponsorship. After several meetings, the young team found experts at BU3 who envisaged this technology without investing in its development confirms interests (Ct→Ke and Ke→Ce) for a product under development and gives its requirements at various occasions (Ke→Ct). BU3 joining the team, as a buyer it has strong influences on the project orientation. First it reshapes the Technology-Environment fit to be explored in a project granted by the Innovation Department: it should integrate two other architectures competing with the one using the technology pursued. This creates tensions as the two other associates originally aimed at a generic product (for BU3 but also its competitors) initially explored *with* the technical help of BU3 rather than *for* a specific development. BU1 managers will insist several times including the first gate-meeting that the two business models have to be explored. The team consolidates progressively and refines these Technology-Environment fits with calculations, risk analysis and market analysis until it copes with the Innovation Department requirements to grant a budget. Among them, the Innovation Department asks for an estimation of the TRL of the technologies needed. Finally at the gate meeting several architectures crossed with several markets seem many possibilities, the strategy to address them has to be clarified. The TRL are quite low but it is accepted.

IV. SUMMARY OF THE FINDINGS

A. SYNTHESIS ON PROPOSITION 1

Considered alone Technology Readiness Levels (TRL) definitions are eventually fixating, this varies greatly from an organisation to another, but this lack of genericity could be compensated by repeating the assessment to various couples [single technology; single environment]. In fact the low TRL can be generic to both technologies and environments focusing on genericity, while the high TRL are assigned to T-E couples rather than technologies in order to fixate on risk reduction. TRL assessment then first codifies the knowledge on one or several considered Technology-Environment couples (actual TRL), second it measures the remaining unknown and deduces the part of this unknown that will be explored by Technology supplier (efforts to reach contracted TRL) and the part that will be explored by its buyer (efforts from contracted TRL to TRL9). Doing so, TRL become a prescriptive model for technology development. This confirms previous research interpretation of TRL as a stage-gate process model (Högman and Johannesson 2013). Depending on the TRL definitions adopted Technology suppliers are then more or less exposed to fixation. Our empirical cases show that before any objective TRL assessment is performed, TRL are over-estimated.

Hence generativity which conditions the process of sourcing innovation, that is TRL assessment, can be characterized as following

- <u>new objects:</u> ***technologies and their intended environments are transformed into the overall system, ruptures in the identities of technologies are likewise whereas identities of environments are mostly stable;***
- <u>new knowledge:</u> ***the technical interfaces at the initial Technology/Environment boundary are explored, creating knowledge on the overall system***

B. SYNTHESIS ON PROPOSITION 2 AND 3

In the petroleum industry organization, ***TRL avoid fixation on a low maturity technology***. The other fixations are results of other reasoning than TRL assessment. The cases also reveal different conceptions of TRL assessment: either it measures the risk that unknown-unknowns (blind spots) remain or it makes a start for an effective risk assessment.

TRL are not an obstacle at genericity. In the aeronautics organization cases, Technology and Environment are unknown, unstable. This is not the case the most described in procedures but, as reviewed here upon, our real cases are grounded in an organization whose TRL procedure focuses on genericity at lower TRL. Aero2 and Aero3 are in accordance with the procedure as several Technology-Environment couples are explored with major consideration on demonstrating technologies. However, the multiple environments belong to one or two business unit out of twelve; hence the variety of the environments could be increased. Aero3 presents more variety of the environments through the workshop. More importantly, the Innovative Buyers that this case presents adopt radically new practices regarding purchasing management. They did not use TRL in this experience of sourcing innovation.

TRL may fixate when actors wait that a certain TRL has been reached to explore the potential value created by the technology in their environment. Aero2 illustrates this well, when the performance ambitioned by the supplier is used to investigate the opportunity, the defixating role that had the Ct→Ke operator was allowed because actors did not proceed a formal TRL assessment to confirm the validity of such results. Overestimating TRL is also instrumental as such.

TRL have no role in defixating and guiding designers in a generative way compared to the supplier-buyer relationship and their individual interests. TRL formalize that the development efforts have been done in a right way.

Finaly, we should clarify that the notion of environment used in TRL methodologies differs from ours. In their conception, that is the tradition of engineering, environment refers to the conditions of a test such as “representative environment” or “laboratory environment”. The main focus of TRL is on the viability of tests. ***The different environments that are described in the definitions of TRL are most of the time different prototyping methods of one single intended final environment. This is detrimental to generativity because the analysis of real cases with our framework shows that the advanced operators between Technology and Environment spaces are the most helpful in overcoming fixation.***

V. Sourcing Innovation? Conclusion, Limitations and Perspectives

Genericity is one way to enact generativity (Kokshagina et al. 2014) and Technology Readiness Levels (TRL) are not incompatible with it. A greater difficulty of TRL is that they provoke the buyer’s temptation to wait until a satisfying TRL has been reached to explore the value creation potential of new technologies starting mutual fixation through waiting games. Hence TRL do formalise the unknown and coordinate who explores what between supplier and buyer, but they do not guide them in maximising generativity, i.e. the key competence for Sourcing Innovation according to design theories. We observed the first experiences of a twelve-business-unit-wide organisation at implementing Sourcing Innovation: either appointing *innovative buyers* among the purchasing teams or conducting *Technology-Environment innovative design workshops*. Both of them have to be refined which should be an opportunity for scholars in various fields such as innovation management, purchasing management, open innovation, marketing management and design theories. The latter have been useful in characterising the innovation situations of our cases with the recent Technology-Environment framework. It might be further improved, for instance our cases suggest to introduce the taxonomy of knowledge by Foray and Lundvall (1996) [know-how, know-who, know-what] in the framework as know-who appeared crucial while often neglected. Also the cases illustrate how the Technology-Environment boundary changes depending on both the definition of the artefact being designed but also upon organisational and relationship considerations which had been neglected. Also this study opens the door to quantitative studies which would be powerful in comparing a large number of firms.

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VII. APPENDIX

C. TRL DEFINITIONS DETAILED ANALYSIS

	Does the TRL scale fixate on a single technology...				
TRL	at NASA?	at DOD?	at DOE?	O&GP?	AeroP?
1	No statement	1 "this technology"	1 "the technology"	No statement	No statement
2	No statement	No statement	"basic principles"	No statement	No statement
3	"the concept"	1 "the Technology"	1 "the technology"	1 "Concept"	No statement
4	No statement	Several "System concepts"	"technological components"	1 "Prototype"	1
5	"From one to-several new technologies"	No statement	1 "The system tested"	1 "Prototype"	1
6	"several-to-many new Technologies"	1 "a Prototype"	1 "The Prototype"	1 "Prototype"	1
7	No statement	1 "a prototype system"	1 "an actual system prototype"	1 "Prototype"	1
8	No statement	1 "the system in its final Configuration"	1 "The technology"	1*	1
9	No statement	1 "Actual application of the technology in its final form"	1 "The technology is in its final form"	1*	1

*text purposefully hidden

	Does the internal TRL scale fixate on a single target Environment (E)...				
TRL	at NASA?	at DOD?	at DOE?	O&GP*?	AeroP?
1	No E	No E	No E	No E	No statement
2	Several "practical applications"	1 or several "practical applications" "the application"	1 or several "practical applications" "the application"	Several "potential applications"	Several
3	No statement	No statement	No statement	No statement	No statement
4	Several "potential	1 or several "bread-	No statement	No statement	No statement

	system applications”	board(s)”			
5	Several “applications”	1 “a simulated environment”	1 “the final application”	No statement	No statement
6	1 “representative model or prototype system”	1 “a relevant environment”	1 “The Prototype”	No statement	No statement
7	1 “an actual system prototype demonstration in a space environment”	1 “an operational environment (e.g., in an aircraft, in a vehicle, or in space)”	1 “the test environment”	1 “an operating system”	1
8	No statement	1 “the system in its final Configuration”	1 prototyped intended E “actual waste in hot commis-sioning”	Several “application cases” OR 1 “for more than N years” // “2 representative cases”	1
9	No statement	1 “Actual application of the technology in its final form”	1 “the actual system”	No statement // “several successful field operations” in procedure	No statement

D. DECISIVE EXTRACTS OF TRL PROCEDURES IN OUR ANALYSIS

6. *NASA SYSTEMS ENGINEERING HANDBOOK*

NASA (2007). NASA Systems Engineering Handbook, DIANE Publishing.

a) Generativity

The technical team selects the best design solution from among the alternative design concepts, taking into account subjective factors that the team was unable to quantify as well as estimates of how well the alternatives meet the quantitative requirements; the maturity of the available technology; and any effectiveness, cost, schedule, risk, or other constraints

The purpose of systems engineering is to make sure that the Design Solution Defnition Process happens in a way that leads to the most cost-effective final system. The basic idea is that before those decisions that are hard to undo are made, the alternatives should be carefully assessed, particularly with respect to the maturity of the required technology

Whether system models are used or not, the design concepts are developed, modifid, reassessed, and compared against competing alternatives in a closed-loop process that seeks the best choices for further development.

Similarly, it is incumbent upon the technology maturation process to identify requirements that are not feasible and development routes that are not fruitful and to transmit that information to the architecture studies in a timely manner.

The fist step in developing a uniform TRL assessment (see Figure G-5) is to define the terms used. It is extremely important to develop and

If the architecture and the environment have changed, then the TRL drops to TRL 5—at least intially. Additional testing may need to be done for heritage sys tems for the new use or new environment. If in subsequent analysis the new environment is suffiently close to the old environment, or the new architecture suffiently close to the old architecture then the resulting evaluation could be then TRL 6 or 7, but the most important thing to realize is that it is no longer at a TRL 9.

b) Supplier-buyer oordination

It is imperative that there be a continual interaction between the technology development process and the design process to ensure that the design reflects the realities of the available technology and that overreliance on immature technology is avoided

continual interaction between the technology development process and the design process ensures that the design reflects the realities of the available technology. This interaction is facilitated through periodic assessment of the design with respect to the maturity of the technology required to implement the design

The purpose of the architecture studies is to refine end-item system design to meet the overall scientific requirements of the mission. It is imperative that there be a continuous relationship between architectural studies and maturing technology advances.

c) Prescriptive model

After identifying the technology gaps existing in a given design concept, it will frequently be necessary to undertake technology development in order to ascertain viability. Given that resources will always be limited, it will be necessary to pursue only the most promising technologies that are required to enable a given concept.

If requirements are defied without fully understanding the resources required to accomplish needed technology developments then the program/project is at risk. Technology assessment must be done iteratively until requirements and available resources are aligned within an acceptable risk posture. Technology development plays a far greater role in the life cycle of a program/project than has been traditionally considered, and it is the role of the systems engineer to develop an understanding of the extent of program/project impacts

d) Risk

There is a tendency on the part of technology developers and project management to overestimate the maturity and applicability of a technology that is required to implement a design

7. *DOD TECHNOLOGY READINESS ASSESSMENT (TRA)*

Assistant Secretary of Defense for Research and Engineering (ASD(R&E)) (2011). Technology readiness assessment (TRA) Guidance. U.S. Department of Defense. Washington DC.

a) Risk focus rather than generativity

A key benchmark is that the technologies of the program be demonstrated in a relevant environment at MS B or at a subsequent Milestone if there is no MS B for this program. If this benchmark is not achieved, a waiver by the MDA is possible, but this waiver must be based on acceptable means of risk mitigation, such as inclusion of an alternative more mature technology as a funded option.

In case of technologies not demonstrated in a relevant environment, determines whether the PM’s proposed risk-mitigation plans are adequate and, in turn, determines whether to issue a waiver

The PM

– Assesses the technological risk in his/her program.

– Plans and ensures funding of the program’s risk-reduction activities to ensure that technologies reach the appropriate maturity levels prior to being incorporated into the program baseline design. The SME team should make recommendations to the PM (with associated rationale) on the candidate technologies that should be assessed in the TRA

TRLs will be used as a knowledge-based standard or benchmark but should not substitute for professional judgment tailored to the specific circumstances of the program.

The PM should include an overview of the system, […] and examples and instructions for determining whether technologies have been demonstrated in a relevant environment.

The PM should prepare an initial list of potential technologies to be assessed.

When competing designs exist, the PM should identify possible technologies separately for each design.

b) Collaboration

The PM [Program Manager]

[…]

– Provides technical expertise to the SME team as needed

The CAE/PEO and S&T Executive

– Approves the PM’s TRA plan and assigns additional participants as desired.

Subject matter expertise and independence from the program are the two principal qualifications for SME team membership. Members should be experts who have demonstrated, current experience in the relevant fields. […] SME team members might be required to sign non-disclosure agreements and declare that they have no conflicts of interest.

c) Critical technologies

The PM [Program Manager] […]

- Identifies possible critical technologies for consideration by the SME team

The CAE/PEO and S&T Executive

[…]

– Reviews and approves the list of critical technologies that pose potential risk to program success and that are to be assessed in the TRA.

The SME [Subject Matter Expert] team

[…]

- In conjunction with the PM and ASD(R&E), reviews the PM-provided list of critical technologies to assess and recommends additions or deletions.

8. DEFENSE ACQUISITION GUIDE BOOK

(2012). Defense Acquisition Guidebook. Defense Acquisition University.

a) Generativity

Generally, this review [the Alternative System Review] assesses the preliminary materiel solutions that have been evaluated during the Materiel Solution Analysis phase, and ensures that the one or more proposed materiel solution(s) have the best potential to be cost effective, affordable, operationally effective and suitable, and can be developed to provide a timely solution to a need at an acceptable level of risk. Of critical importance to this review is the understanding of available system concepts to meet the capabilities described in the Initial Capabilities

Document (ICD) and to meet the affordability, operational effectiveness, technology risk, and suitability goals inherent in each alternative concept. Additionally, competition across the alternatives should be evaluated and discussed.

Therefore, the ASR [Alternative System Review] should identify key system elements that two or more competing teams will prototype prior to Milestone B.

The ASR identifies the most promising path forward; however; there is still the understanding that both the requirements and the system may evolve until Milestone B.

b) Critical Technologies

If a platform or system depends on specific technologies to meet system operational threshold requirements in development, production, operation, and sustainment, and if the technology or its application is either new or novel, then that technology is considered a critical or enabling technology. If there are any critical technology elements, they are to be evaluated during the Technology Development phase to assess technology maturity.

c) Collaboration

Technology Development is a focused effort to mature, prototype, and demonstrate technologies in a relevant environment. This results in a preferred system concept that achieves a level suitable for low risk entry into Engineering and Manufacturing Development. This can best result from a close collaboration between the science and technology community, the user, and the engineering community

9. DOE Technology Readiness Assessment Guide

DOE (2009). Technology Readiness Assessment Guide.

a) Fixation

Projects with concurrent technology development and design implementation run the risk of proceeding with ill-defined risks to all components of the project baseline. In support of technology development, it usually follows that a roadmap is developed to provide the technology development path forward for successful deployment of the selected technology.

The next step in this effort involves selecting equipment that meets or most closely meets the performance requirements or criteria. [...] During this activity, the available equipment is compared and those identified as most closely meeting the defined requirements are selected for further evaluation.

Equipment and or process evaluation involves experimental or pilot facility testing of the process or equipment identified in the selection process. Although selection identified those processes and equipment that most closely meet design requirements, it is not uncommon for evaluation of those selected processes and equipment to identify areas where the process or equipment fails to meet requirements. In those cases, it may be necessary to return to the selection of alternatives to modify or select another preferred option.

The recommended guidance is to conduct TRAs during conceptual design and preliminary design processes;

The mission need is independent of a particular solution and should not be defined by equipment, facility, technological solution, or physical end item. The focus for technology development assessments, at this stage, should be on a clear statement of the requirements of the input and the desired output of the process, to include the safety strategy input, as applicable and appropriate

Advantages [of TRL] include:

[…]

- Assist in selecting the best technology alternative.

b) Risk focus

TRAs and TMPs are effective management tools for reducing technical risk and minimizing potential for technology driven cost increases and schedule delays.

In the realm of project management, TRAs and the resulting TMPs can be used as a project management tool to reduce the technical and cost risks associated with the introduction of new technologies.

The TRL values above (in parenthesis) at each CD point are recommended minimum values. DOE programs should justify and document through risk management processes deviations from the recommended minimum TRLs at each CD based on their particular technology's complexity and associated risks, as deemed applicable and appropriate The TRA should not be considered a risk assessment, but it should be viewed as a tool for assessing program risk and the adequacy of technology maturation planning by the program/project.

Technology maturity is a measure of the degree to which proposed CTEs meet program objectives and can be related to program risk.

c) Critical technologies

Identifying the Critical Technology Elements (CTEs). CTEs are the at-risk technologies that are essential to the successful operation of the facility, and are new or are being applied in new or novel ways or environment A technology element is "critical" if the system being acquired depends on this technology element to meet operational requirements (with acceptable development cost and schedule and with acceptable production and operation costs) and if the technology element or its application is either new or novel, or in an area that poses major technological risk during design or demonstration. Said another way, an element that is new or novel or being used in a new or novel way is critical if it is necessary to achieve the successful development of a system, its acquisition, or its operational utility.

d) Collaboration

Developing a Technology Maturation Plan (TMP). If the TRL level for a CTE does not meet the expectation level at each Critical Decision level (especially for CD- 2 and later), then a maturity level gap exists that requires further evaluation testing or engineering work in order to bring the immature technology to the appropriate maturity level. The development or revision of a Technology Maturation Plan (TMP) identifies the activities required to bring immature CTEs up to the desired TRL (see section 5.0 for more details on the TMP).

The process of technology development, in accordance with the program/project's technology development plans and any TMPs issued as a result of a prior TRA, should ensure that all CTEs have reached at least TRL 6, which indicates that the technology is ready for insertion into detailed design, as applicable and appropriate.

e) Generativity

This DOE-wide model has the following attributes: it includes (a) "basic" research in new technologies and concepts (targeting identified goals, but not necessarily specific systems), (b) focused technology development addressing specific technologies for one or more potential identified applications, (c) technology development and demonstration for each specific application before the beginning of full system development of that application,

Review of Alternatives

Results of technology development assessments and studies are documented and reviewed to determine the validity of the approach that best meets project goals, objectives, and the physical, functional, performance, and operational requirements of the project at the best value; to include testing and validation of all required functions, including any safety functions.